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LCA application in the optimum design of high rise steel structures

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ABSTRACT

The Life Cycle Assessment tool is used in the construction industry to assess the environmental impact and the resources that are used throughout the life span of a construction project, which consists of the raw material acquisition, production, design phase, construction phase, operation phase and the demolition and dismantling phase. The global community is taking immediate action to reduce the CO_2 and green house gases (GHG) that are being produced due to global warming. The Kyoto protocol agreement has set binding targets for 37 industrialized countries and the European community to reduce their GHG emissions by an average of 5%, back to 1990 levels, within the years of 2008–2012.

The global community is making many efforts to reduce CO_2 and green house gases (GHG). The building construction industry is responsible for approximately 40% of the carbon dioxide emissions. There are currently more than four super tall, more than 100 story, high rise building construction projects in metropolitan Seoul, and this ranks Korea in the top four countries worldwide for the number of high rise buildings. Reducing the amount of structural steel in these high rise buildings by using an optimum structural design would reduce CO_2 and green house gas (GHG) emissions. This aim of this study was to analyze the lateral load resisting structural systems in a high rise steel building in order to select the optimum structural system under the equivalent allowable lateral drift. The environmental impact was assessed using the LCA tool, and the results are discussed along with possible recommendations that may improve the current LCA tools.

Contents

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1. Introduction

1.1. Research background

Abrupt climate change due to global warming and other environmental catastrophes are continuously threatening human life. The Kyoto protocol is in effect to reduce GHG (green house gas) emissions by an average of 5% within the years of 2008–2012 in 37 countries and within the European community in order to obtain the emission levels measured in 1990. In order to achieve this challenging goal, environmental considerations and sustainable design approaches need to be integrated into a number of different types of decisions that are made by architects, engineers, business entities, public administrations and policymakers. Established evaluation methods include the Life Cycle Assessment (LCA), Strategic Environmental Assessment (SEA), Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA), Cost-Benefit Analysis (CBA), Material Flow Analysis (MFA), and Ecological Footprint. This study mainly focuses on LCA research [1].

The LCA is a tool that is used to assess the potential environmental impacts of and to identify the resources that are used throughout the life cycle of a product, which include the raw material acquisition, production and use phases, as well as waste management [2,3]. In the building industry, the LCA identifies the potential environmental impacts that may occur in the design, construction, operation and maintenance, and the demolition and dismantling phases. Life Cycle Assessment is a comprehensive assessment and considers all attributes or aspects of the natural environment, human health, and resources [2,3].

There are four phases in an LCA study, which are goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. The goal and scope definition phase includes the study motivation, the intended application, and the intended audience [2]. This phase is also when the system boundaries of the study are described and the functional unit is defined. The functional unit is a quantitative measure of the functions that the goods (or service) provide. The LCI phase results in a compilation of inputs (resources) and outputs (emissions) of a product throughout its life-cycle in relation to the functional unit. The LCIA phase is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of the system [2]. In the interpretation phase, the results from the previous phases are evaluated in relation to the goal and scope of the study in order to reach conclusions and offer recommendations [2].

Life Cycle Assessment is a methodology that is used in many countries to calculate the environmental loadings of buildings, including the $LCCO_2$ and the GHG emissions, which can then be converted to $LCCO_2$. Parts of active LCA tools that have been developed are the SBTool, which was developed by Natural Resource Canada and the International Initiatives for a Sustainable Built Environment (iiSBE), LEED, which was developed by the United States Green Building Council (USGBC), BREEAM, which was developed in the UK, and CASBEE, which was developed by the Japan Sustainable Building Consortium. These tools can assess the environmental impacts of buildings throughout their entire life cycle. Optimum structural system design can reduce the quantity of structural steel that is used in constructing buildings, which would result in reduced $LCCO_2$ emissions. An efficient lateral load resisting structural system can reduce the amount of structural material, which can then reduce the $LCCO_2$ and GHG emissions.

1.2. Literature review regarding Life Cycle Assessment

Life Cycle Assessment (LCA) and various energy generation models have interrelationships. The amount of energy consumption will influence the result of the LCA. Recent research on LCA and energy models are reviewed in this section. LCA and LCCA models were developed and the life cycle energy, emissions and cost inventory was established for potential power generation technologies in Singapore. Power generation from clean/renewable power generation technologies are costlier than fossil fuel based power generation. However, their low environmental impacts can compensate for unfavourable economics if environmental externalities become an accepted paradigm in appraisal [4]. The non-combustion based renewable electricity generation technologies were assessed against a range of sustainability indicators and using data obtained from the literature. The indicators used to assess each technology were price of generated electricity, greenhouse gas emissions during full life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts. The cost of electricity, greenhouse gas emissions and the efficiency of electricity generation were found to have a very wide range for each technology, mainly due to variations in technologies options as well as geographical dependence of each renewable energy source [5]. A Life Cycle Assessment (LCA) has been performed based on data related to an Italian wind farm: production and deliver of energy and raw materials, components manufacturing, transports, installation, maintenance, disassembly and disposal have been analyzed. The attention focused to those life cycle steps generally neglected or not adequately investigated as installation, civil works and maintenance. The results can be assumed as representative of the Italian context and they can represent a further incentive to the diffusion of wind farms [6]. Energy is a vital input for social and economic development of any nation. With increasing agricultural and industrial activities in the country, the demand for energy is also increasing. Formulation of an energy model will help in the proper allocation of widely available renewable energy sources such as solar, wind, bioenergy and small hydropower in meeting the future energy demand in India. The different types of models such as energy planning models, energy supply-demand models, forecasting models, renewable energy models, emission reduction models, optimization models have been reviewed and presented. Also, models based on neural network and fuzzy theory have been reviewed and discussed [7]. In the race against climate change, aiming for low-carbon competitiveness, Flanders has initiated a carbon neutrality strategy on industrial parks, building towards energy efficient buildings and processes, acting as a stimulus for the production and consumption of green electricity. However, premises and internal process optimization on industrial parks is not considered sufficient to limit greenhouse emissions in Flanders. Structural transition is called for, aiming for industrial clustering and energy autonomy based on renewables [8]. Renewable energy systems (RESs) have been promoted for rural electrification as an answer to the growing energy needs of communities while simultaneously satisfying environmental and resource

scarcity problems. These off-grid systems however have several challenges in the perspective of sustainability due to the technically and financially weak recipients and users of the projects. This paper aimed to further understand the challenges and social impacts of rural electrification projects using RES through a case study of a centralized off-grid solar plant in the Philippines [9]. A comprehensive overview of the life cycle GHG emissions from wind and hydro power generation has been presented, based on relevant published studies. Comparisons with conventional fossil, nuclear and other renewable generation systems are also presented, in order to put the GHG emissions of wind and hydro power in perspective. Studies on GHG emissions from wind and hydro power show large variations in GHG emissions, varying from 0.2 to 152 g CO_2-equiv. per kWh. The main parameters affecting GHG emissions are also discussed in this article, in relation to these variations [10]. Electricity is conceivably the most multipurpose energy carrier in modern global economy, and therefore primarily linked to human and economic development. Energy sector reform is critical to sustainable energy development and includes reviewing and reforming subsidies, establishing credible regulatory frameworks, developing policy environments, through regulatory interventions, and creating market-based approaches. This multitude of aspects play a role in societal debate in comparing electricity generating and supply options, such as cost, GHG emissions, radiological and toxicological exposure, occupational health and safety, employments, domestic energy security, and social impressions [11]. The state of the art in designing renewable energy systems [12–18] specifically solar-based energy system, ground source-based system and day-lighting system have been reviewed to gain optimum performances in sustainable buildings. Efficiency of each of these systems in reducing resource consumption was evaluated. Geometric conditions have a determining effect on the performances of solar-based energy system and day-lighting system. In solar-based energy system, designing factors, such as system selection, building's orientation, installation location, area of installation, tilt angle and surface temperature, are needed to be considered. Factors of day-lighting system, such as fenestration option, material, area or size, shape, orientation, position, ceiling and shading devices, are needed to be designed carefully to optimize the quality of the luminous environment for occupants. For ground source-based energy system, season condition, operating condition, mode of system, selection of compressor, ground heat exchange, pump, are important to improve system's performance and reduce cost [12].

1.3. Research objective

This study investigated the effects that lateral load resisting structural systems have in reducing the amount of steel required in steel construction high rise buildings.

A steel high rise building is often modelled using a finite element method of structural analysis. Lateral load resisting structural systems are designed and modelled for structural analysis. Three different lateral load resisting structural systems were modelled. The three systems included:

A. Reference model
B. Braced frame (X and Chevron bracing)
C. Out-rigger system

The structural analysis and design software called MIDAS-Gen was used to create the structural designs of the three different cases that had a limited lateral drift of less than $H/400$ (H is the total height of the structure).

The aim of this study was to examine how reducing the amount of steel material used in high rise steel buildings would impact the environment. Based on the structural design results, the generation of $LCCO_2$ was analyzed using the LCA tool in order to investigate the overall environmental impact. Suggestions of necessary improvements were made in regard to the application of the LCA tools in designing high rise steel buildings.

2. Structural systems of high rise buildings

The computation of lateral drift is an important process when designing high rise buildings that are based on lateral loads such as earthquake or wind loads that are imposed throughout the height of the building. Lateral load resisting structural systems are designed to contain robust stiffness in order to resist lateral drift. In this study, the braced frames of X bracing and Chevron bracing systems and the outrigger system were investigated.

2.1. Braced frame

A braced frame is a vertical cantilever truss that supports structural elements with flexural stiffness. This lateral load resisting system is utilized in high rise buildings that are at least 30 stories tall. The system has a relatively large degree of stiffness compared to its material strength.

One of the structural characteristics of this system is that it has high ductility and low rigidity with the pin connection, which allows the system to resist the lateral loads efficiently. The system is efficient because the diagonal members are absorbing the axial tension or compression forces.

2.2. Outrigger system

The outrigger system performs as a cantilever wall or a truss that connects the core-braced frame to the exterior columns. Inner columns in the braced frame consist of vertical members in horizontal trusses that connect the columns of the core to the exterior columns.

Boundary conditions consist of the rigid connections in the core and the pin connections in the exterior columns.

In a previous study, Taranath [19] suggests that the suitable location of an outrigger is at the point of 0.455 times the building height when designing a one-outrigger system, and at the points of 0.312 and 0.685 times the building height when using two outriggers.

3. Research methodology

3.1. Description of the pilot model building and selection of the LCA tool

The pilot model building was based on a J building in a B-project. The gravity load was calculated and applied to the high rise steel building based on the local building code. The wind load was also applied to the building facade and was based on the wind pressure that was computed using the average wind velocity of Sung Nam, Korea.

Life Cycle Assessment methods can be divided into two categories, the building material and component combinations (BMCC) and the whole process of the construction (WPC) [5]. Life Cycle Assessment based on BMCC refers to the environmental loading and the impacts that the materials and energy used throughout the entire life cycle of the building may have on the environment. The WPC includes the qualities of life of the occupants of the building, as well as the cultural and social impacts that the building may have. The WPC can be used in making decisions and can be used as a supporting tool in designing and constructing an environmentally friendly building [20].

Table 1
Parameters and indicators of the key study issues on energy use and environmental loading.

Issues	Parameters	Indicator [unit]
Energy and resource consumption	Non/renewable energy	Embodied energy per unit area for unit year [GJ/m^2 yr]
	Electrical peak demand for facility operation	The peak monthly electric demand [MJ/m^2]
	Minimal use of materials (finishing/virgin)	The percentage of above-grade interior floor, wall, and ceiling surface areas [%]
	Potable water	Site area not/requiring watering [m^2]
Environmental loading	Greenhouse gas emissions	CO_2 equivalent emissions per kg/m^2 of gross area [GJ/m^2 yr]
	Other atmospheric emissions	Emissions of GHG equivalent per year in kg per unit area
	Solid waste	Volume of solid waste [m^3]
	Water use	Estimated total water use [L/day]

In this study, the tools were LCA tools that dealt with WPC, including SBTool, LEED, CASBEE, and BREEAM tools. The SBTool was especially utilized in this study because of its well-organized evaluation system and quantitative parameters. However, the SBTool needed to be further developed for application to tall buildings.

This study examined how the LCA application can be improved upon in regard to its use for high rise buildings and to see if it is feasible to use the SBTool application for high rise buildings.

3.2. Parameter analysis of SBTool

The SBTool consists of seven aspects, as follows:

A. Site selection, project planning and development
B. Energy and resource consumption
C. Environmental loadings
D. Indoor environmental quality
E. Service quality
F. Social and economic aspects
G. Cultural and perceptual aspects

The issues of energy and resource consumption and environmental loading are related to the structural systems of buildings. Table 1 shows the parameters of these two issues, which were calculated or derived using the indicators listed. The parameters such as embodied energy, electrical peak demand and GHG emission, are based on either the unit area or the gross area of the buildings. For this reason, the total volume or weight of the structure itself is never considered in any of the parameters, except for the solid waste parameter. It is assumed that the parameters are related to the total volume or the weight of the building or to the construction phase. When a reduction of material use is achieved due to the adaption of an optimum structural system, the environmental impacts should be examined.

4. Case study

4.1. Summary of the study building and its limitations

The study building was the J building of the B-project in Korea. Using this building, the design scheme cases such as the reference model, which had no lateral load resisting system, and other cases that had adapted lateral resisting structural systems have been modelled and analyzed to compare the quantities of structural materials used in each case. Gravity loads and wind load conditions are shown in Tables 2 and 3, respectively. The allowable maximum lateral drift was 263 mm, which was $H/400$ where H denotes the height of the building.

4.2. Model cases

The structure of the proposed model building was concrete, although in this study, the concrete structure was assumed to be a steel structure for research purposes. The reference model had no lateral load resisting system. The lateral load resisting systems were added to the reference model as shown in Figs. 1–3.

Table 2
Gravity loads.

Load type		Load (kg/m^2)
Dead load	Concrete	250
	Metal deck	15
	Interior/partition	75
	Steel self-weight	50
	Total	390
Live lad	Residential	200
	Total	200

Table 3
Wind load condition.

Region	Wind velocity	Class	Note
Kyeonggi-do (Korea)	25	A	Inland (I)

Case 1: Basic model
Case 2: Braced system (X type)
Case 3: Braced system (Chevron)
Case 4: Outrigger system

4.3. Optimum structural system and material quantity

Limiting the maximum lateral drift to 263 mm, the total steel weights were calculated based on the design results of the different structural systems. The total steel weights according to the structural design results are shown in Table 4 and Fig. 4.

The structural design results indicated that the reference model (Case 1) had the maximum steel quantity, and that the Chevron brace system (Case 3) had the minimum steel weight. Based upon these results, adapting a lateral load resisting structural system for use in high rise buildings can reduce the total weights of steel and other materials used throughout the construction process.

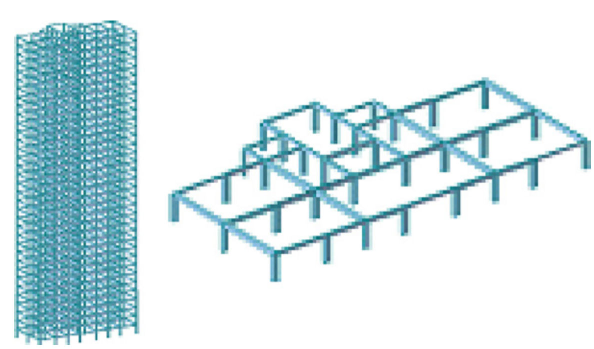

Fig. 1. The reference model without any lateral load system in the typical structure.

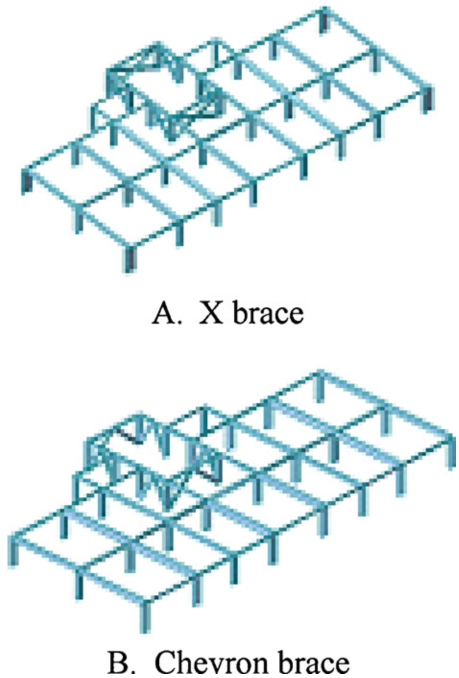

Fig. 2. A model of the braced system (X brace and Chevron brace) in the typical structure.

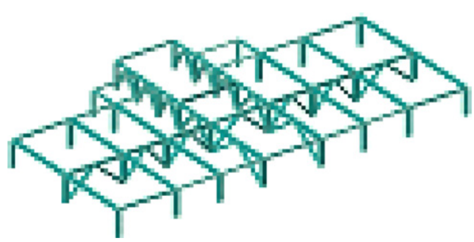

Fig. 3. The model of the outrigger system in the typical structure.

Table 4
The total steel weights and the reduction rates by case.

Case	Total weight of steel [tonf]	Reduction rate [%]
Case 1	2822	–
Case 4	2414	−14.5
Case 2	2137	−24.3
Case 3	2023	−28.3

A study conducted by Cho [21] reports that the reduction rate increases as the building becomes more sensitive to the lateral load. In high rise buildings, the lateral load increases significantly with building height. This fact indicates that the consideration of the structural system in terms of the LCA is important in the evaluations of high rise buildings with respect to environmental impact.

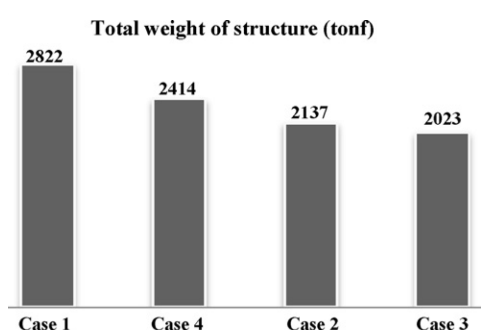

Fig. 4. Comparison of the total steel weight based on the lateral load resisting system.

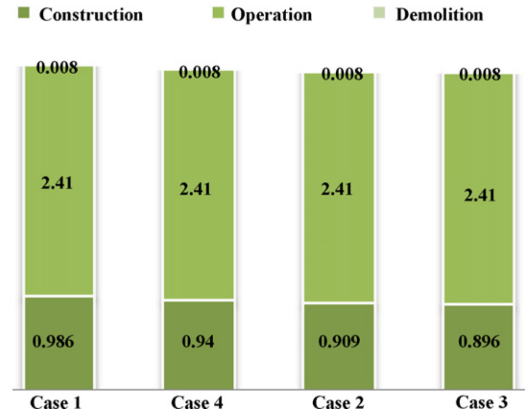

Fig. 5. $LCCO_2$ ($\times 10^7$ kg-CO_2) emissions of the different structural systems.

4.4. Calculation of $LCCO_2$ emissions based on material quantity

Based on the previously calculated weight of the steel used in the construction phase, the $LCCO_2$ emissions (Life Cycle CO_2) were calculated using the SUSB-LCA program. The SUSB-LCA ver. 1.0 is a LCA program used for $LCCO_2$ calculation, and the results of our analysis are shown in Fig. 5. Carbon dioxide emissions during the facility operation phase and the demolition phase were assumed to remain constant for the four cases tested. During the construction phase, the CO_2 emissions ranged from 0.896×10^7 kg-CO_2 to 0.986×10^7 kg-CO_2.

The construction phase of this study building resulted in approximately 30% of its life cycle CO_2 emissions. Existing parameters to estimate $LCCO_2$ emission only reflect the emissions that occur during the operation phase. Thus, the construction phase and demolition phase need to be considered in order to improve the accuracy of estimating $LCCO_2$ emissions. During the construction phase, $LCCO_2$ emissions are generated from the structural materials as they are being manufactured and delivered, and throughout the construction process.

5. Life Cycle Assessment

The adaptation of the structural system was verified to result in a reduction in material weight and in $LCCO_2$ emissions. Life Cycle Assessment was performed using the SBTool [22], an LCA tool, for the four different structural systems.

5.1. Life Cycle Assessment using the existing SBTool [22]

Life Cycle Assessment was performed using the SBTool. In this study, two out of the seven issues were considered. These were the issues that were related to the material quantity and the environmental loading that were affected by the adaptation of the structural systems, energy and resource consumption and environmental loading.

Fig. 5 shows the results of the LCA. In regard to energy and resource consumption, the score was 1.2 in energy and resource consumption and 1.6 in environmental loading when the full score was 5.0. The detailed categories and parameters of these two issues are shown, along with their scores, in Table 5. Bolded characters are associated with the volume of the structure, a factor which is reducible by structural system.

Table 5
Categories and parameters of the study issues with regard to assessment score by SBTool (Case 1: Reference model).

Issue (score)	
Categories (score)	Parameters (score)
B. Energy and resource consumption (0.9)	
B1 Total life cycle non-renewable energy (0.26)	B1.1 Annualized non-renewable primary energy embodied in construction material (0.09) B1.2 Annual non-renewable primary energy used for facility operation (0.11)
B2 Electrical peak demand for facility operation (0.11)	
B3 Renewable energy (−0.11)	B3.1 Use of off-site energy (−0.5) B3.2 Provision of on-site energy (−0.5)
B4 Materials (0.57)	B4.1 Minimal use of finishing materials (−0.11) B4.2 Minimal use of virgin materials (0.18) B4.3 Use of durable materials (0.29) B4.4 Use of bio-based products obtained from sustainable sources (−0.17) B4.5 Use of cement-supplementing materials in concrete (0.26) B4.6 Use of materials that are locally produced (−0.11) B4.7 Design for disassembly, re-use or recycling (0.34)
B5 Potable water (0.36)	
C. Environmental loading (1.59)	
C1 Greenhouse gas emissions (−0.03)	C1.1 Annualized GHG emissions embodied within construction materials (−0.25) C1.2 Annual GHG emissions from all energy used for facility operations (0.02)
C2 Other atmospheric emissions (0.43)	C2.1 Emissions of ozone-depleting substances during facility operations (2.44) C2.2 Emissions of acidifying compounds (0.3) C2.3 Emissions leading to photo-oxidants (0.42)
C3 Solid waste (0.23)	
C4 Rainwater, stormwater and wastewater (0.12)	
C5 Impacts on the site (0.66)	
C6 Other local and regional impacts (0.18)	
Total score (2.49)	

5.2. Parameters that are affected by structural system

Assessments were performed on Case 2, Case 3, and Case 4 using the structural systems. The following parameters were related to the energy that was embodied within the materials, which change depending on which structural system was used. Table 6 lists the variables of each parameter. The parameters were:

B1.1 Annualized non-renewable primary energy embodied in the construction materials
B4.1 Minimal use of finishing materials
B4.2 Minimal use of virgin materials
C1.1 Annualized GHG emissions embodied in the construction materials

Parameter B1.1 shows the highest difference between Case 1 and Case 3. Case 1 generated a 1.8% while Case 3 resulted in 19.2%. Parameters B4.1 and C1.1 had the same scores for all of the tested cases. This result was due to the insufficient influence of the structural system (Table 7).

5.3. Total Life Cycle Assessment of the energy and resource consumption and environmental loading categories structural system

The total life cycle non-renewable energy score ranged from 0.26 to 0.42 based on the structural system chosen. As the structural material quantity increased, the score tended to decrease significantly. That is, one of the parameters within this category, embodied energy, was dependent upon the total structural volume, which varied based on which structural system was used.

Material scores ranged from 0.57 to 0.54. The areas of virgin material and finishing material use in relation to the total material used decreased. It was assumed that the rate of decreasing area for virgin or finishing materials was relatively smaller than that of the decreasing rate for the total material used (Fig. 6).

*B1: Total life cycle non-renewable energy
B2: Electrical peak demand for facility operation
B3: Renewable energy
B4: Materials
B5: Portable water
C: Environmental loading

5.4. Proposal to add parameters for high rise structural systems in SBTool

It has been found that the structural system choice has a significant impact on the total amount of materials used and $LCCO_2$ and other GHG emissions. Thus, the assessment results showed that some parameters related to material quantity can be influenced to a significant degree in SBTool.

For this reason, a parameter added through the adaptation of a structural system needs to be able to be added to the existing SBTool in order to assist with the development of the optimum structural

Table 6
Parameters that varied by structural system.

Parameter ID	Variable [unit]
B1.1	Embodied energy [GJ/m^2]
B4.1	The percentage of areas consisting of exposed structural elements [%]
B4.2	The percentage of areas consisting of non-virgin materials [%]
C1.1	The annual amount of CO_2-equivalent emissions [kg/m^2 yr]

Table 7
Weighted scores (when the full score was 5.0) of the parameters in Table 6.

	B1.1	B4.1	B4.2	C1.1
Case 1	225 (0.09)	8 (−0.11)	30 (0.18)	40.9 (−0.25)
Case 4	201.67 (0.52)	7 (−0.11)	27 (0.14)	36.4 (−0.25)
Case 2	184 (0.83)	7 (−0.11)	25 (0.12)	33.5 (−0.25)
Case 3	178 (0.96)	6 (−0.11)	24 (0.11)	32.3 (−0.25)

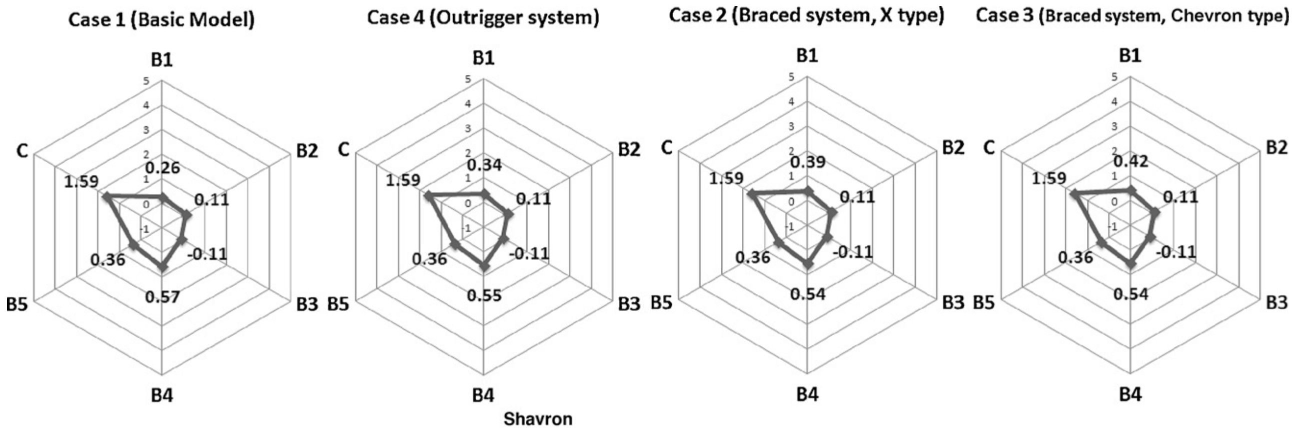

Fig. 6. Assessment results for the B categories, energy and resource consumption, and category C, environmental loading.

Table 8
Proposed parameters for optimum structural system development in SBTool.

Intent	To suggest the optimum structural design that will minimize the direct and indirect material use and $LCCO_2$ or GHG emissions	
Indicator	The percent reduction in emissions and material use	
Information sources	Use structural analysis and design software to derive the total structural weight of each structural system	
Benchmarks	Reduction rate is under 5%	−1
	Reduction rate is more than 5% but less than 10%	0
	Reduction rate is more than 10% but less than 20%	3
	Reduction rate is over 20%	5

system that results in the minimum $LCCO_2$ and GHG emissions and uses the least amount of materials.

Table 8 lists the proposed specifications of the parameters that will be used to assist with the development of the optimum structural system.

These parameters will be effective during the pre-design or design phases. Other alternatives are presented with their scores to help determine which structural system to use.

One limitation of this process was that only the structural issue was considered, and the cooling and heating load was excluded. As a result of the decrease in structure volume, items such as beams, columns, walls or slabs, which may be significant $LCCO_2$ and GHG emission factors, were not accounted for in the operation phase. In future studies, this problem should be considered in order to derive an accurate evaluation parameter throughout the whole life cycle of the construction process.

In the proposed evaluation, the use of the structural analysis and design program was required in order to calculate the reduction rate of the structural weight. It was also necessary to set up a library of reduction rates in the evaluation program, for convenience and independence. For this reason, the tool needs to be able to establish a quantitative correlation between the reduction rate and the scale of the structure, the type of structure, such as reinforced concrete, steel, or composite, and the structural system in order to establish reasonable benchmarks for the parameters.

6. Conclusion

In this study, structural system models were designed to control for a lateral drift of 263 mm using a structural analysis and design program. The total weight of the structure was calculated, and, based on this weight, the $LCCO_2$ was calculated. From this result, the optimum design scheme was determined, taking into account the fact that the total weight of the structure depended on the lateral load resisting system. Finally, each case was evaluated with the LCA tool, SBTool. The following conclusions resulted from this study.

1) The optimum design in this case study for the study building was the Chevron brace frame system, which had 799 tonf less material, corresponding to a 28.3% reduction from the reference model.
2) In SBTool, there were parameters that are related to the optimum design of the structural system. These parameters were components of energy and resource consumption and environmental loading.
3) SBTool evaluations were conducted for the four test cases and the results showed that the Chevron brace frame system obtained the highest score of 2.91 which is adapted to the optimum structural system and minimum score in the reference model by 2.78, which is the maximum weight of the structure among cases.
4) In SBTool, the addition of the parameters of the optimum structural system would result in the use of the minimum amount of material in the pre-design and design phases.
5) Future studies should take into account the reduction rate according to the scale of the structure, the shape of the structure, and the effects of heating and cooling load.

Acknowledgements

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